Report for 2002WV5B: WRI48-Impact of Longwall Mining on Headwater Streams in Northern West Virginia

- Book Chapters:
  - Longitudinal profiling of headwater streams pg. 76-94 in: Functions of Headwater Stream Systems. Technical Information Workshop, North American Benthological Society, Athens, GA.
- Other Publications:
  - Impacts of longwall mining on the diversity, lingevity and functionality of benthic macroinvertebrate communities in central Applachian headwater streams. Presented at: 51st Annual Meeting of the North American Benthological Society, Athens, GA.

Report Follows:

Impact of longwall mining on headwater streams in northern West Virginia

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Abstract

The purpose of this study was to measure the impact of longwall mining on headwater streams in northern West Virginia. Physical, chemical, and biological measurements were collected at eight sites along the gradient of each stream from the source 0.65km (0.4 miles) downstream. Six longwall mined streams were compared to five reference streams that were unmined or had been room-and-pillar mined.

Physically, longwall mined headwater streams were significantly different in terms of stream width and temperature. Longwall mined streams were dry at 28% of sites, and all streams were impacted near their sources with stream width indicating remnant surface flow. Streams reemerged downstream, with most reappearing gradually along the downstream gradient. Stream width returned to reference conditions in four of six longwall mined streams in watersheds greater than 80 acres. Instantaneous stream temperatures were consistently 1-2^{o}C cooler in longwall mined compared to reference streams, indicative of underground flow following stream subsidence.

Longwall mined streams were similar in terms of pH and hardness, but significantly different in terms of alkalinity, conductivity, and dissolved oxygen when compared to reference streams. Compared to reference streams, higher conductivity and oxygen demand are indicative of somewhat degraded conditions in longwall mined headwater streams. However, longwall mined streams were capable of supporting a diverse macroinvertebrate fauna at sites where water was present.

Reference streams had diverse and ubiquitous aquatic macroinvertebrate communities across the region. Semivoltine taxa, those requiring perennial flow conditions for multiple years, were collected at 98% of reference stream sites. In contrast, longwall mined streams were dry at 28% of sites and had semivoltine taxa at only 48% of sites. Longwall mining results in a 50% reduction in the omnipresence of perennial aquatic biological communities in headwater streams in Marshall County.

The functional disposition of the macroinvertebrate communities in longwall mined streams failed to follow the predicted trends exemplified by communities in reference streams. For instance, leaf shredders constitute ½ of all taxa and ½ of all individuals collected in the upper reaches near the source of reference streams. Shredders declined precipitously to 30% of the community in the lower reaches of reference streams. In longwall mined streams shredders often dominated in the mid-reaches of streams, with resurgence of surface water apparently mimicking the spring source condition. Predators were often out of balance with the community in longwall mined versus reference streams.

In conclusion, de-watering due to longwall mining results in a 50% reduction in the perennial headwater stream condition in Marshall County, West Virginia. Loss of headwater streams from an increasingly large area within the landscape could significantly disrupt ecosystem-level processes in the central Appalachian region.

Introduction

Longwall mining in the central Appalachian region results in loss of many springs and wells such that mining companies are generally required to replace water supplies. Studies of wetlands (Schmid & Kunz, 2000) and larger streams (Earth Science Consulants, 2001) in southwestern Pennsylvania, USA have addressed the impacts of full-extraction mining followed by subsidence on these respective landscape elements, but no studies have addressed impacts on spring-fed headwater streams in the region. These streams are often ignored or mistakenly referred to as "intermittent" or "ephemeral" due to their non-existence on widely-used 1:24,000 scale topographic maps. In fact, headwater streams can be expected to comprise greater than 80% of the total length of the stream network in a region draining a given watershed (Hynes, 1970).

Loss of headwater streams from the landscape could have significant eco-system level consequences. Headwater streams are more recently being regarded as exceptional in terms of performance in energy flow and nutrient retention within the complex network of forest and stream interrelations (Wallace *et al*, 1997). For instance, the stream-dwelling seal, spring, and northern two-lined salamanders are the dominant vertebrate predators in these headwater streams, but many other amphibians also depend on headwater streams to provide suitable aquatic breeding sites in proximity to the forest. Other fauna, including birds, depend on the emergence of aquatic insects as a significant food source (Jackson & Fisher, 1986; Gray, 1993). Via their biological communities, headwater streams have the unique capacity to import low-quality, lignin and cellulose forest products (leaves and sticks) and convert that material into high-quality fats and proteins for export back to the forest in the form of insect emergence. Moreover, emerging insects are in a form readily consumed by a suite of forest species at a time coinciding with annual breeding and nesting cycles.

The purpose of this research is to measure potential impacts of longwall mining to headwater streams in northern West Virginia. In order to accomplish this we developed and evaluated a method for assessing damage to headwater streams based on attributes of the biological community along the headwater stream gradient. We tested the hypothesis of no significant difference in the diversity, longevity, functionality, and ubiquity of the aquatic macroinvertebrate communities when comparing longwall mined versus reference headwater streams.

Methods

Field studies consisted of sampling streams at their source and at measured downstream intervals. Selection of suitable study streams was accomplished by determining the presence or absence of longwall undermining from mining maps and permit records filed with State Department of Environmental Protection field offices. Within each mining region, longwall mined watersheds were paired with nearby reference watersheds that were geographically similar, but were either un-mined or room and pillar mined several decades prior to study. Studies were conducted in four Pennsylvania mining regions and one West Virginia mining region operated by different companies over the past two-decades.

In the field each stream was sampled by a four-person team on a single date. Each stream was followed to the primary source and the source location recorded using Global Positioning Systems. The source (spring, or seep) was sampled for pH, conductivity, dissolved oxygen, and temperature using standardized field meters. Stream width was measured 10 times using a ruler or tape. Three investigators collected aquatic macroinvertebrates from a ten meter reach using any means practical (hand-picking, nets, pans, forceps) for a total of 10 minutes (timed). The resulting 30-minute composite sample was stored in a pre-labeled 250 ml plastic container, preserved in 80% ethanol, and returned to the laboratory. The team measured fifty meters downstream with a tape, recorded the GPS location, and repeated the sampling. Sampling continued at 100 meter intervals for a total of eight samples per stream. Sampling was conducted in May through July, 2002, laboratory work in July through December, and analysis from January through June, 2003.

In the laboratory (210b Donahue Hall, WJU), macroinvertebrates from stream samples were sorted and identified to the lowest practical taxonomic level, generally genus. Chemical and biological data were compiled in spreadsheets and analyzed. Community-level metrics included taxa richness (number of kinds) as a measure of diversity, the number of EPT (mayfly, stonefly and caddisfly) taxa as an indication of the purely aquatic, relatively long-lived (generally >9 months aquatic) taxa, and the number of semivoltine taxa, those with aquatic larval life cycles that are greater than one-year in length as an additional biological measure of stream permanence. The percent abundance of each of four functional feeding groups (leaf shredders, fine particle collectors, algal grazers, predators) was calculated in order to compare the trophic status (energy balance) of communities at each site (Merritt & Cummins, 1996). Basin geomorphology including watershed area (Allan, 1995), stream elevation, slope, and aspect were measured for each site using GPS coordinates and MapTech Software with US Geological Survey 1:24,000 scale data.

In analysis 8 samples collected along the longitudinal stream gradient represented each stream. Samples site locations were randomly predetermined based on prescribed distance measurement from the source. Samples collected at regular (50, 100 meter) intervals were representative of the 0.65km (0.4 mile) headwater stream watershed-ecosystem. Six mined and five reference streams were compared using two-way general linear models analysis of variance of streams within regions. With the exception of six outliers, data met ANOVA assumptions of normality and homogeneity.

Index of ubiquity

Widespread occurrence, omnipresence, or ubiquity of macroinvertebrate taxa were measured mathematically by creating a Ubiquity Index. The purpose of the Ubiquity Index was to predict the occurrence of various macroinvertebrate taxa across the study region (Map 1), and to compare disturbed versus reference conditions to determine if any taxa appeared particularly responsive to longwall mining. The index is based on the presence or absence of taxa in samples (88) from streams (11) across replicate regions (4). Two replicate reference regions, separated by approximately 25 km, included 2 Dysart Woods compared to 3 Marshall County streams. Three recently disturbed streams in Marshall County, separated by approximately 2 km from 3 streams that were longwall mined 5-10 years ago, comprised the two replicate disturbed regions. Given the 25 and 2 km difference in scale, the ubiquity of a given taxa would be expected to favor the replicate disturbed regions.

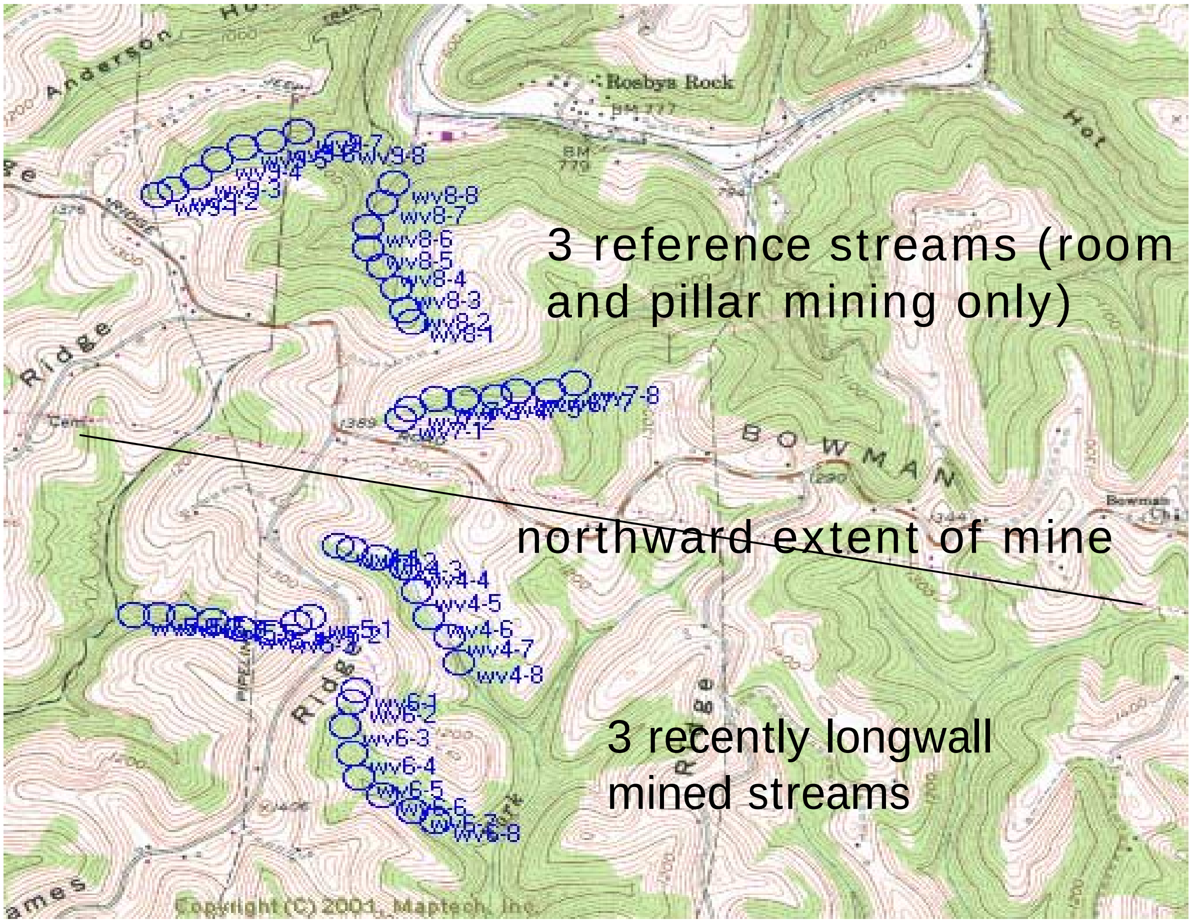
The Ubiquity Index was calculated separately for disturbed versus reference conditions for each of 60 macroinvertebrate taxa, as well as the summary variables EPT Taxa, Semivoltine Taxa, mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera) using the formula:

$$U_{taxa} = \left(\left(\text{region 1}(f_{streams} * f_{samples}) + \text{region 2}\,(f_{streams} * f_{samples})\right) /2 \right) * f_{region}$$

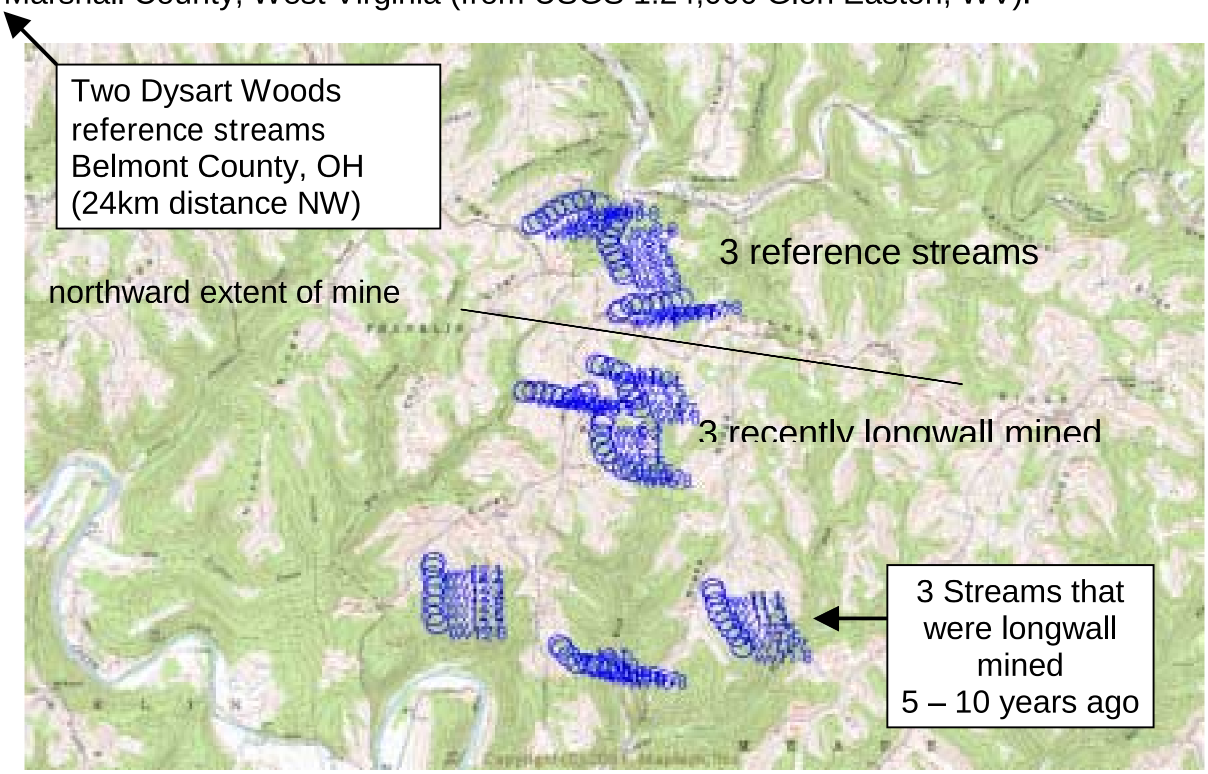
where the ubiquity of a given taxa (U_{taxa}) is the product of the precent frequency of occurrence (presence/absence) of the taxa in samples, streams, and regions. Frequency of occurrence in streams ($f_{streams}$) is equal to the percent of streams (3, except 2 in Dysart Woods Reference) in a region that a taxa was collected in. The variable $f_{samples}$ is the percent frequency in 24 samples (except 18 in Dysart Woods) within a region. The product of the stream and sample frequency is averaged for the two regions and multiplied by the frequency of occurrence of the taxa in the two regions (*i.e.* f_{region} = 100%, 50%, or 0% occurrence in the two regions).

Study sites

Three reference streams in Marshall County that had been room and pillar mined were compared to three streams that had been recently longwall mined (Map 1). Three Marshall County streams that had been longwall mined between 5 and 10 years prior to the study were also sampled (Map 2). Two unmined reference streams were sampled in Dysart Woods, approximately 26 km to the northwest of the Marshall County reference sites.



Maps 1 & 2. Sampling locations in recently longwall mined and reference streams in Marshall County, West Virginia (from USGS 1:24,000 Glen Easton, WV).



Results

Physical characteristics of study streams

Physical attributes of streams and their valleys were comparable between longwall mined and reference watersheds (Table 1). One of the Dysart Woods reference streams merged with a larger watershed resulting in a stream width of 2.5 meters, an extreme outlier (Figure 1). Otherwise, physical data were normally distributed and homogenous. One statistically significant physical difference was that longwall mined streams were on average 1.5^{o} C cooler than reference streams at the time of sampling. Streams that had been longwall mined within the past two years had lower water temperatures than streams that had been longwall mined 5-10 years ago (Figure 1).

The average watershed area upstream of sampling sites was not significantly different in longwall mined versus reference streams (Table 1). Watershed drainage area ranged from 4.3 to 262 acres at sampling sites in reference watersheds and 3.7 to 116 acres at sites in longwall mined streams. The average sampling point in longwall mined watersheds was in a stream draining 47 acres of land surface area compared to 60 acres in reference streams. Dysart Woods reference streams (streams 1 & 2) joined larger streams to form 191 to 262 acre watersheds (Figure 1). Data from larger stream sites in Dysart Woods were not used in scatter plots because there were no sites in longwall mined streams representing watershed areas that large.

Table 1. Mean (and 1 Standard Deviation) physical attributes of samples from longwall mined (N=48) versus reference (N=40) watersheds (ANOVA, Dunnett's Test ,*p<0.01).

	Reference streams		Longwall mined streams	
	Mean	(SD)	Mean	(SD)
Watershed area (acres)	60.4	(66.6)	47.4	(32.4)
Elevation (feet)	1098	(98)	1090	(90)
Stream slope (%)	11.3	(6.6)	11.1	(6.5)
Compass heading (degrees true N)	181	(109)	167	(50)
Median stream width (m)	0.88	(0.41)	*0.58	(0.45)
Water temperature (^{o}C)	18.1	(1.5)	*16.5	(1.7)

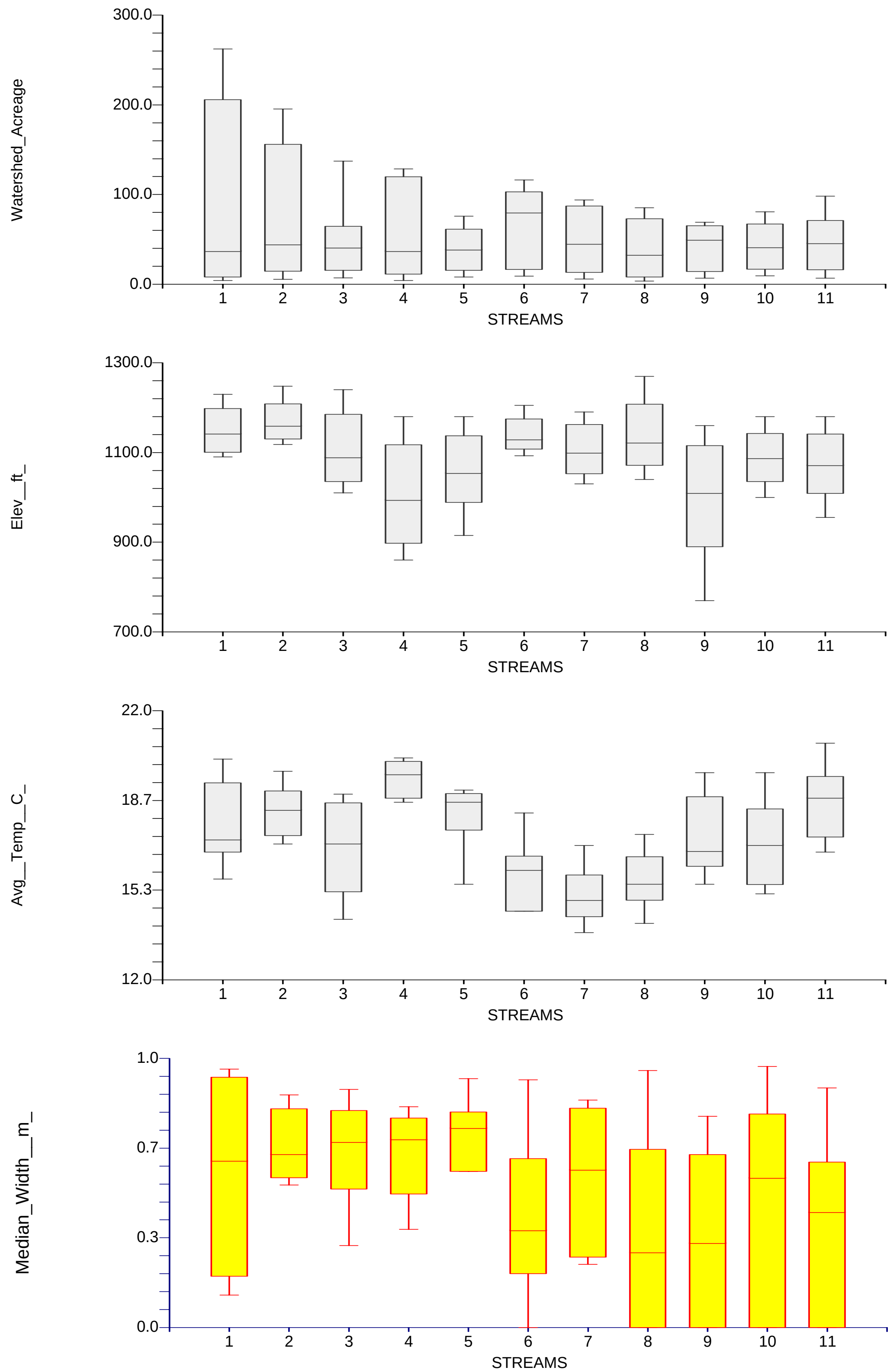


Figure 1. Box plots of median physical attributes of samples (N=8) from reference streams in Dysart Woods (streams 1-2) and Marshall County (3-5), and longwall mined streams that were recently longwall mined (6-8) or had been longwall mined over the past decade (9-11) in Marshall County.

Average stream slopes, elevations, and compass headings in longwall mined watersheds were comparable to reference watersheds, and standard deviations were indicative of sampling across variable terrain (Table 1). Elevation ranged from 1270' to 770' amsl, with mean elevation near 1100' in both disturbed and reference watersheds. Streams originated as spring seeps at approximately 1200' elevation. Reference stream 4 and disturbed stream 9 were the only watersheds with samples collected below 900' elevation, thus the scope this study includes relatively high elevation unnamed tributary streams. This study excluded larger, named streams within the region that occurred between 900' and 623', the mean pool elevation where Fish Creek enters the Ohio River.

Streams originated as spring seeps averaging less than 0.5 m width and draining 3.7 to 9.3 acre watersheds at elevations between 1160 to 1270' (Table 2, Figure 2). Watershed area at the point of flow origin was not statistically different when comparing longwall mined and reference streams (p=0.39). Reference watersheds drained 5.8 acres at the point of flow origin and longwall mined streams drained 6.9 acres. Four out of six origin points in longwall mined streams were dry. Some longwall mined streams were either dry, as indicated by zero stream width, or partially dewatered as evidenced by narrower stream widths in the upper reaches. Dry streambeds were conspicuous in the field and the former spring seep origins were obvious.

Table 2. Mean (and Standard Deviation) physical attributes of samples at the point-of-origin of longwall mined (N=6) versus reference (N=5) watersheds (ANOVA, Dunnett's Test ,*p<0.01).

	Reference streams		Longwall mined streams	
	Mean	(SD)	Mean	(SD)
Watershed area (acres)	5.8	(0.85)	6.9	(0.77)
Elevation (feet)	1198	(14.8)	1216	(16.2)
Stream slope (%)	0.217	(0.028)	0.183	(0.025)
Heading (degrees)	181	(40)	167	(37)
Median stream width (m)	*0.44	(0.09)	0.10	(0.90)

Excluding dry streams, median stream widths in longwall mined watersheds were not statistically different than stream widths in reference watersheds (Table 1). However, stream profiles indicate that where water was present stream width was notably less in streams that drained the upper 20 acres of longwall mined watersheds (Figure 2). Median stream widths ranged from 0 to 0.4 meters in the upper 20 acres of longwall mined watersheds, versus 0.1 to 1.4 meters in the upper 20 acres of reference watersheds. Most of the subsided longwall mined headwater streams re-emerged at points downstream as indicated by the steeply inclining regression line representing the relationship between stream width and watershed area in longwall mined streams (Figure 2). Re-emergence restored stream width to near-reference conditions in four of six longwall mined streams. The intersection of the regression lines for longwall mined versus reference streams indicates that stream width returned to background conditions once an average longwall mined watershed had achieved 80+ acres in drainage area.

The physical effects of dewatering were most apparent near the spring seep sources where all longwall mined streams were affected to some degree. Water returned to most longwall mined streams as their watersheds approached 20 acres in drainage area. In 20 acre watersheds longwall mined streams were about ½ the width of reference streams. Interpolating from Figure 2, longwall mined streams achieved 5/8 the width of reference streams in 40 acre watersheds, and 7/8 of reference stream widths in 60 acre watersheds. The gradual increase of stream width indicates that surface water re-emerges continuously along the gradient of longwall mined headwater streams.

Stream temperature at the time of sampling (instantaneous) was consistently lower in longwall mined versus reference streams (Figure 2). On average, stream temperature was approximately $1^{o}C$ lower where water was present in the upper reaches of longwall mined streams, and $2^{o}C$ lower in the lower portions of the watersheds. Statistically significant differences in water temperature are particularly compelling because the field sampling schedule eliminated seasonal effects by alternating randomly between longwall mined and reference streams.

In contrast, the tendency for stream temperature to increase with increasing stream size, as indicated by the slopes of the regression lines, was the result of two obvious factors. First, streams were sampled consistently starting at the point of origin in the morning and working downstream into the afternoon. Thus the apparent temperature increases actually reflect daily warming of the streams. Second, streams in the upper reaches of watersheds are proportionally dominated by groundwater and reflect a tendency toward mean annual temperature of $12^{o}C$. There was less of a tendency for longwall mined streams to exhibit the downstream temperature increases measured in reference streams. Consistently lower instantaneous temperatures in longwall mined streams is apparently due to subsidence which results in reduced exposure to the surface conditions evident in reference streams. Temperatures well above mean annual temperature in longwall mined streams also reflect a relatively short groundwater residence time which is further evidence that re-emergence of subsided headwater streams occurs continuously along the downstream greadient and mostly within the scope of this study, that is, watersheds less than 100 acres in drainage area.

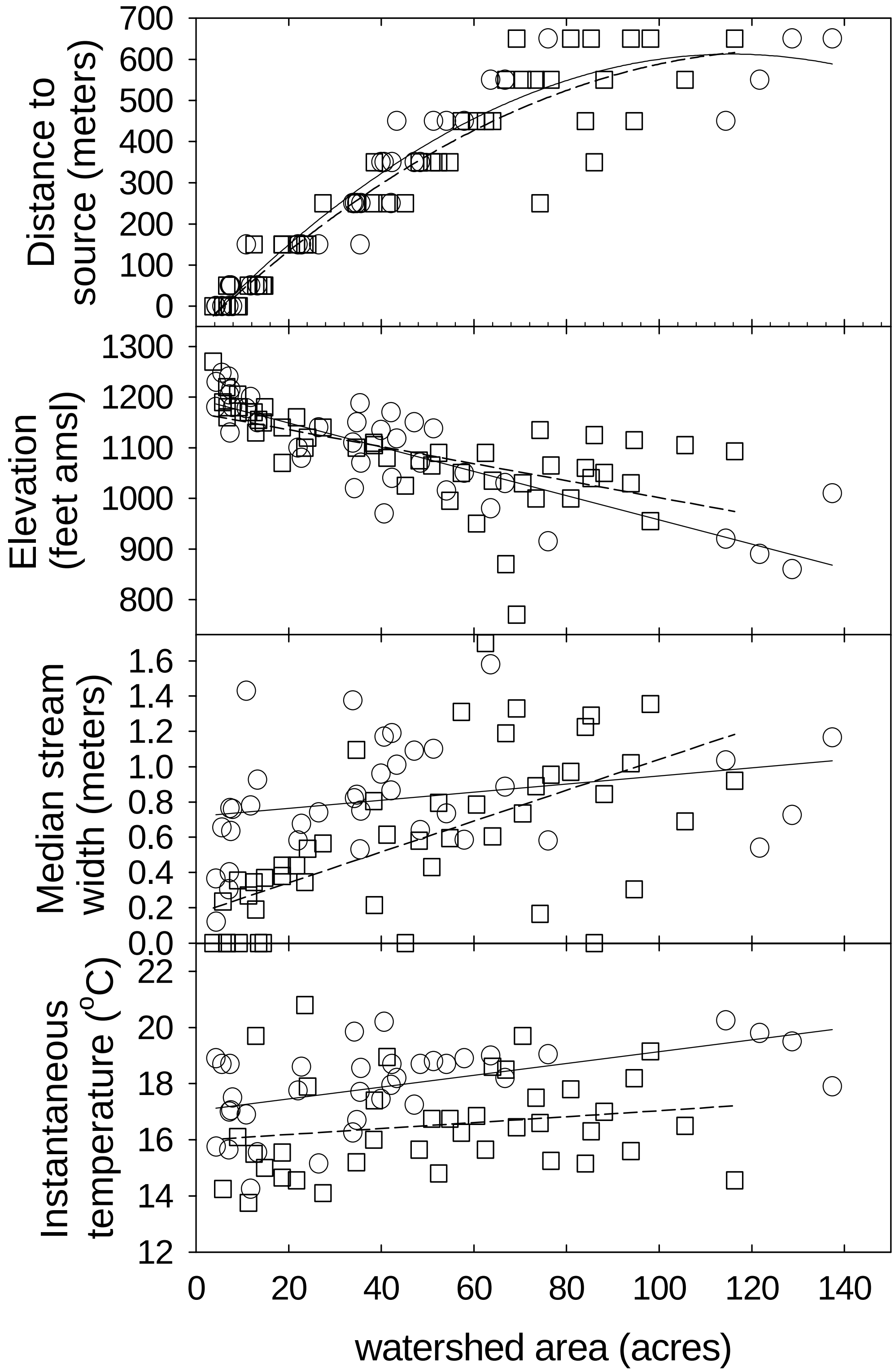


Figure 2. Profiles of physical attributes versus watershed area of longwall mined (squares) and reference streams (circles). Least squares means linear regression lines for longwall mined (dashed, N=48) and reference (solid, N=40) streams.

Chemical characteristics of study streams

Water chemistry was significantly different for three of the five chemical parameters measured in the field (Table 3). Stream water pH, compared as the mean of the log of the hydrogen ion content, was on average 7.7 in longwall mined and reference streams. Water hardness (Ca^{2+}, Mg^{2+}, Fe^{+2}, Mn^{2+}), primarily calcium, was not significantly different when comparing disturbed versus reference watersheds.

Mean conductivity, dissolved oxygen, and alkalinity showed statistically significant differences between longwall mined and reference streams (Table 3). Average conductivity values were approximately 100 micro mhos greater in longwall mined streams, indicating a 29% greater dissolved ion content in longwall mined streams. Reference streams were on average 88% saturated with dissolved oxygen, and longwall mined streams averaged 78% saturated. Alkalinity, primarily bicarbonate (HCO_3^-), averaged 79 parts per million greater in longwall mined streams, a 60% increase compared to reference streams.

Table 3. Mean (and 1 Standard Deviation) water chemistry in samples from longwall mined (N=48) versus reference (N=40) watersheds (ANOVA, Dunnett's Test ,*p<0.01).

	Reference streams		Disturbed streams	
	Mean	(SD)	Mean	(SD)
pH (mean H^+ conc.)	7.67	(0.32)	7.71	(0.31)
Conductivity (uhmos)	344	(89)	*446	(65)
Dissolved oxygen (% sat.)	87.8	(14.6)	*78.3	(16.7)
Alkalinity (ppm)	131	(35)	*210	(45)
Hardness (ppm)	175	(44)	161	(20)

There was little difference when comparing pH across regional streams (Figure 4). Most pH values were between pH 7 to pH 8. There was a significant ($p<0.05$), $r^2=0.33$) downstream trend of increasing pH with increasing stream size (Figure 5). There was a greater pH difference between the two Dysart Woods reference streams, streams 1 and 2, than there was across the region. Stream 1 had an average pH (as log H^+ concentration) of 7.8 versus 7.2 in stream 2 (Figure 4). Stream 2 also had comparatively low conductivity and alkalinity, particularly at the two uppermost sites near the source (Figure 5). Stream 2 pH, conductivity, and alkalinity achieved levels comparable to other reference streams at a distance of between 350 and 450 meters from the source. The increase in dissolved mineral content was accompanied by an exceptionally low dissolved oxygen reading 350 meters below the source. Greater oxygen demand at this site is indicative of mineral-laden spring water entering the stream system. The pH of longwall mined streams was within the range of natural differences in pH among regional reference streams. At the watershed-level, lower pH values near the source of streams are apparently the result of CO_2-charged groundwater at the source coupled with a relatively high oxygen demand by the heterotrophic stream community.

Significantly greater mean conductivity and alkalinity were indicative of greater dissolved mineral content in longwall mined versus reference streams (Table 3). Each stream, including reference streams, appeared to have a unique conductivity signature (Figure 4), but conductivity profiles indicated consistently greater total dissolved solids in longwall mined streams regardless of stream size (Figure 5). Conductivity was highly variable at the point of flow origin and became more consistent downstream. In any given longwall mined stream, resurgence of water downstream of subsided stream segments was accompanied by step-wise increases in conductivity that peaked at 450-550*u*mhos in approximately 80 acre watersheds. The stepped, or incremental pattern parallels that of stream width and helps confirm that most of the surface water lost to subsidence returned to the stream bed as graduated resurgence upwellings in streams draining 80+ acres. Conductivity remained consistently high in all longwall mined streams, with no recovery apparent.

Unlike conductivity, alkalinity showed a tendency toward recovery to background conditions as indicated by convergence of regression lines representing longwall mined versus reference streams. However, regressions of alkalinity versus watershed area for longwall mined and reference streams did not interact within the range of watershed sizes studied here. Therefore, any recovery indicated by convergence of regression lines is predicted to occur well downstream of the scope of this study.

Lower dissolved oxygen in many longwall mined streams near their point of flow origin appears to reflect the observed stagnation of water in partially dewatered stream segments. In the field, we sampled any available pocket of surface water within 5 m of the predetermined and measured sampling point. In larger stream segments somewhat lower dissolved oxygen may reflect chemical oxygen demand in resurgence areas. In a few isolated incidents in the field we noted black or red precipitates indicating formation of metal hydroxides on the streambed. Precipitates were generally confined to stream reaches less than 50 m in length, stream water was always >50% oxygen saturated, and pH was always >7. Lower dissolved oxygen in the headwaters of an average longwall mined stream would be expected to return to near-reference conditions of approximately 90% oxygen saturation as indicated by the interaction of the respective regression lines at a point of approximately 100 acres.

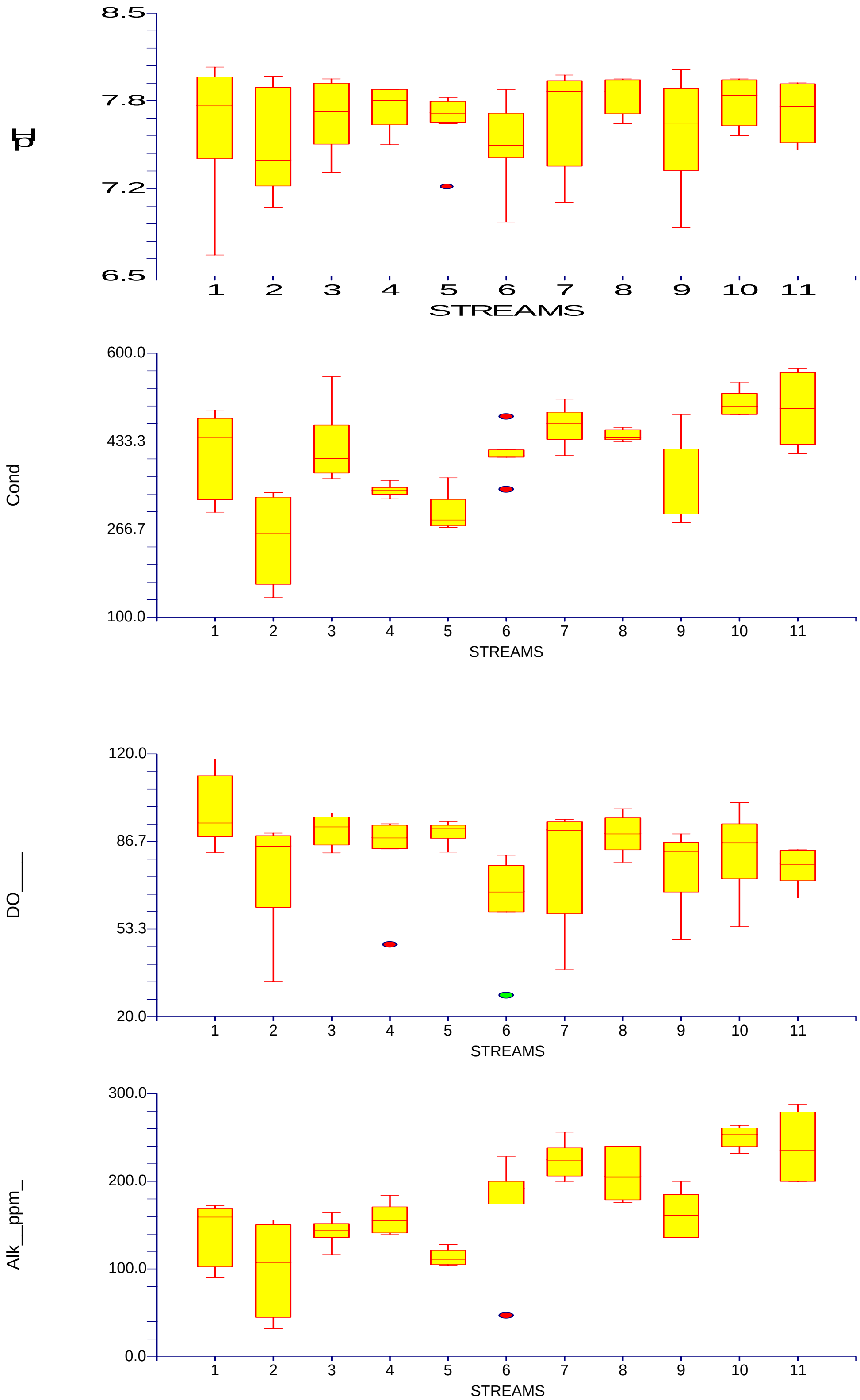


Figure 3. Box plots of median chemical attributes of samples (N=8) from reference streams in Dysart Woods (streams 1-2) and Marshall County (3-5), and longwall mined streams that were recently longwall mined (6-8) or had been longwall mined over the past decade (9-11) in Marshall County.

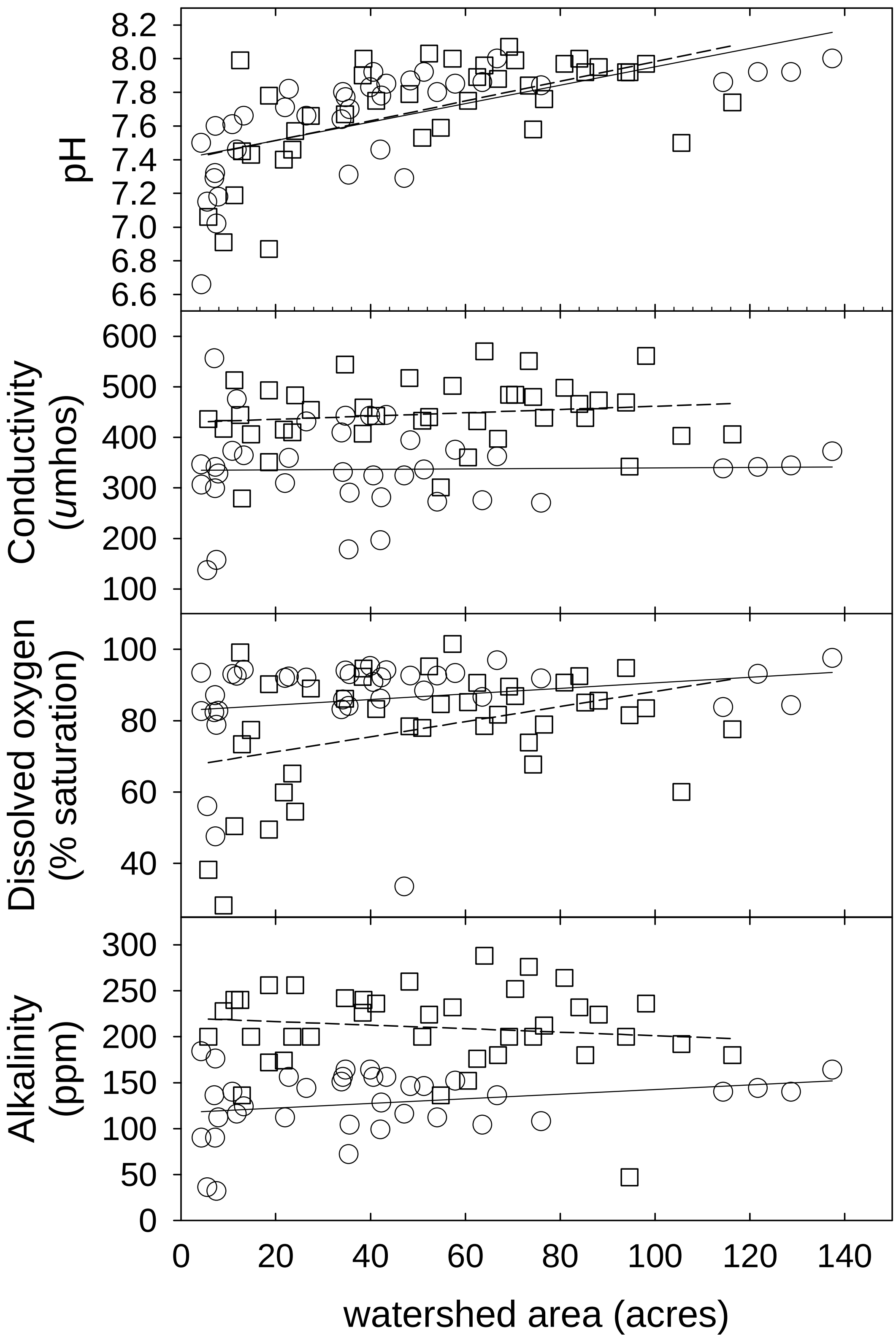


Figure 4. Profiles of chemical attributes versus watershed area of longwall mined (squares) and reference streams (circles). Least squares means linear regression lines for longwall mined (dashed, N=48) and reference (solid, N=40) streams.

Biological characteristics of study streams

Abundance, Diversity, and Longevity of Stream Communities

An average reference stream sample (N=40) was composed of 61 individuals representing 14 different kinds (taxa) of aquatic macroinvertebrates (Table 4). The majority of taxa were EPT Taxa, comprised of mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera). The EPT taxa are relatively long lived, with aquatic development periods lasting from 6 months to more than one year (Anderson & Wallace, 1996). When considered collectively, the overlapping life cycles between 10 different EPT Taxa within the community indicate perennial flow conditions in the average reference streams. Longevity of the biotic community is further indicated by an average of 3 different semivoltine taxa collected in an average reference stream sample.

Significantly fewer organisms were collected from longwall mined than from reference watersheds (Table 4). No surface water was present at 7 of 24 sample locations in recently disturbed streams, and at 7 of 24 sample locations in streams that had been disturbed over the past decade. However, measures of abundance (total number collected), diversity (Richness and EPT Taxa), and longevity (EPT Taxa and Semivoltine Taxa) were reduced by about one-half in longwall mined versus reference streams overall, indicating that dewatering impacts extend beyond the 29% of stream sites that were dry at the time of sampling.

Table 4. Mean (and 1 Standard Deviation) for biological community metrics in samples from longwall mined (N=48) versus reference (N=40) watersheds (ANOVA, Dunnett's Test, *p<0.01).

	Reference streams		Longwall mined streams	
	Mean	(SD)	Mean	(SD)
Total number collected	61.35	(23.67)	*27.35	(28.27)
Taxa Richness (# of kinds)	13.95	(4.43)	*7.04	(5.99)
EPT Taxa (per sample)	9.65	(3.14)	*4.85	(4.57)
Mayflies (taxa per sample)	2.98	(1.39)	*1.63	(1.66)
Stoneflies (taxa)	3.68	(1.33)	*1.75	(1.91)
Caddisflies (taxa)	3.00	(1.41)	*1.48	(1.53)
Semivoltine taxa	3.18	(1.43)	*1.56	(1.76)

Box Plots show that macroinvertebrates were consistently abundant and diverse in samples collected throughout reference streams, but the response of longwall mined streams was more variable (Figure 5). With one exception, longwall mined streams had sample distributions indicating wide-ranging within-stream differences in macroinvertebrate abundance and diversity. In the most highly-impacted stream (Stream 6) less than 10 macroinvertebrates were collected in an average 30-minute composite sample, a collecting rate of one every three minutes compared to one every thirty-seconds in reference streams. In contrast, 10 of 16 samples from two of the least impacted longwall mined streams had abundance and diversity characteristics comparable to reference stream samples. Mean abundance and richness in two longwall mined streams was not significantly different than in two of the reference streams (ANOVA $p<0.05$, Dunnett's test).

All of the longwall mined streams appeared impacted to some degree, but some streams were more affected than others. The biological community in one of the recently mined streams(6) was nearly eliminated. Recently mined stream 7 and previously mined stream 10 were less impacted than other longwall mined streams, with some metrics approaching near-reference conditions. From the source downstream 0.65km, none of the longwall mined headwater streams studied in Marshall County disappeared completely, but all were impacted to some degree.

The EPT Taxa were sensitive to longwall mining. Only three of six longwall mined streams had sample distributions that overlapped reference streams. Recently disturbed stream 7 had between 4 and 10 EPT Taxa throughout the stream. Watershed 10, disturbed in the past, had few EPT Taxa in the uppermost reaches, but a particularly rich fauna at downstream sites resulting in the highest mean EPT Taxa of any stream, and a median EPT Taxa (9) comparable to reference streams. In contrast, the most highly impacted stream had an average of 1 EPT Taxa per sample, typically the mayfly *Paraleptaphlebia sp.* (Ephemeroptera: Leptophlebiidae), but also occasional individuals of the stonefly *Amphinemura delosa* (Plecoptera:Nemouridae), the caddisfly *Neophylax sp.* (Trichoptera:Odontoceridae), Isopods (Isopoda: Aseelidae), dixid and chironomid midges (Diptera: Dixidae, Chironomidae), and snails (Gastropoda: Planorbidae).

Semivoltine taxa, those that require greater than one year in the aquatic larval development phase, were particularly sensitive to dewatering (Figure 5). For instance, semivoltine taxa were completely eliminated from stream 6, and averaged one per sample in the other recently mined streams. Overall, semivoltine taxa comprised 19% of the total number of macroinvertebrates collected in the study, and 18% of the total number of kinds of invertebrates collected in the study. Semivoltine taxa were collected in 39 of 40 reference stream samples. Between 1 and 5 Semivoltine Taxa could be expected in reference stream samples, with an average of 2 to 4 taxa per sample (Figure 5). The most commonly encountered semivoltine taxa (Table 5) included the Dobbsonfly *Nigronia serricornis* (Megaloptera: Corydalidae), the stoneflies *Peltoperla arcuata* (Pelcoptera: Peltoperlidae), *Acroneuria carolinensis* (Plecoptera: Perlidae), and *Agnetina sp.,* (Plecoptera: Perlodidae), and the crayfish *Cambarus bartoni* (Decopoda: Cambaridae).

Streams that had been longwall mined in the past had several semivoltine taxa (Figure 5). Stream 10 was dry for the first 50, had 3 semivotine taxa 150 meters from the source, was dry again at 250 meters, and was well-watered with abundant and diverse benthic community for the next 300 meters including 3 or 4 semivoltine taxa per sample (Figure 6). Semivoltine taxa were absent from the upper reaches of all streams that had been longwall mined. One or two taxa were collected from the mid and lower reaches of two of the three recently mined streams. Two to five semivoltine taxa were collected in the mid to lower reaches of all streams that had been longwall mined in the past. Greater abundance of semivoltine taxa in streams that had been longwall mined sometime in the past is an encouraging indication of potential long-term recovery. However, the sample size is limited to 3 recent and 3 past disturbed streams, and between-stream variability is considerable.

Biological metrics reflecting the relative abundance, diversity, and longevity of macroinvertebrate communities gave consistently negative responses to longwall mining (Figure 6). Impacts appeared to be greatest near points of stream origin, and to lessen somewhat downstream. For instance, by interpolating best-fit regression lines for 10 acre watersheds, macroinvertebrates in longwall mined streams were 77% more difficult to collect, 65% less diverse, had 75% fewer EPT taxa, and had 72% fewer semivoltine taxa than comparable reference streams. Biological metrics in longwall mined streams gradually increased downstream so that in an average 100 acre watershed, again interpolating from regression models, abundance was 31% lower, richness 27% lower, EPT taxa 27% lower, and semivoltine taxa 26% lower than in 100 acre reference streams. Recovery of biological metrics to background conditions is indicated by the slope of the regression lines approaching, but not interescting within the scale of this study. Although risky because it is out of the range of this study, interaction between the longwall mined and reference regression lines, perhaps indicating biological recovery, is predicted to occur at a point somewhere between 158 acres (semivoltine taxa) and 178 acres (taxa richness) for each of the four biological metrics.

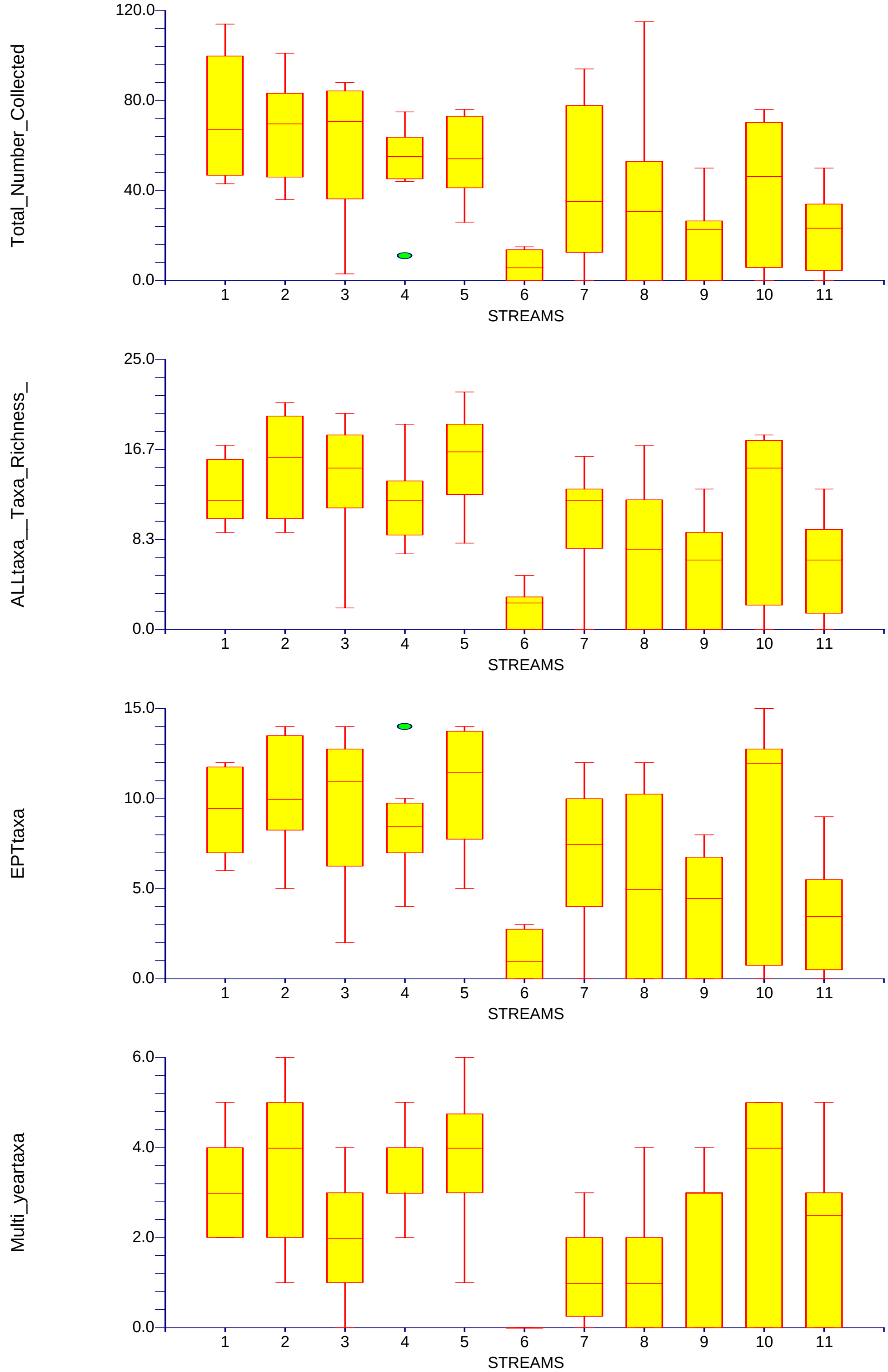


Figure 5. Box plots of median biological attributes of samples (N=8) from reference streams in Dysart Woods (streams 1-2) and Marshall County (3-5), and longwall mined streams that were recently longwall mined (6-8) or had been longwall mined over the past decade (9-11) in Marshall County.

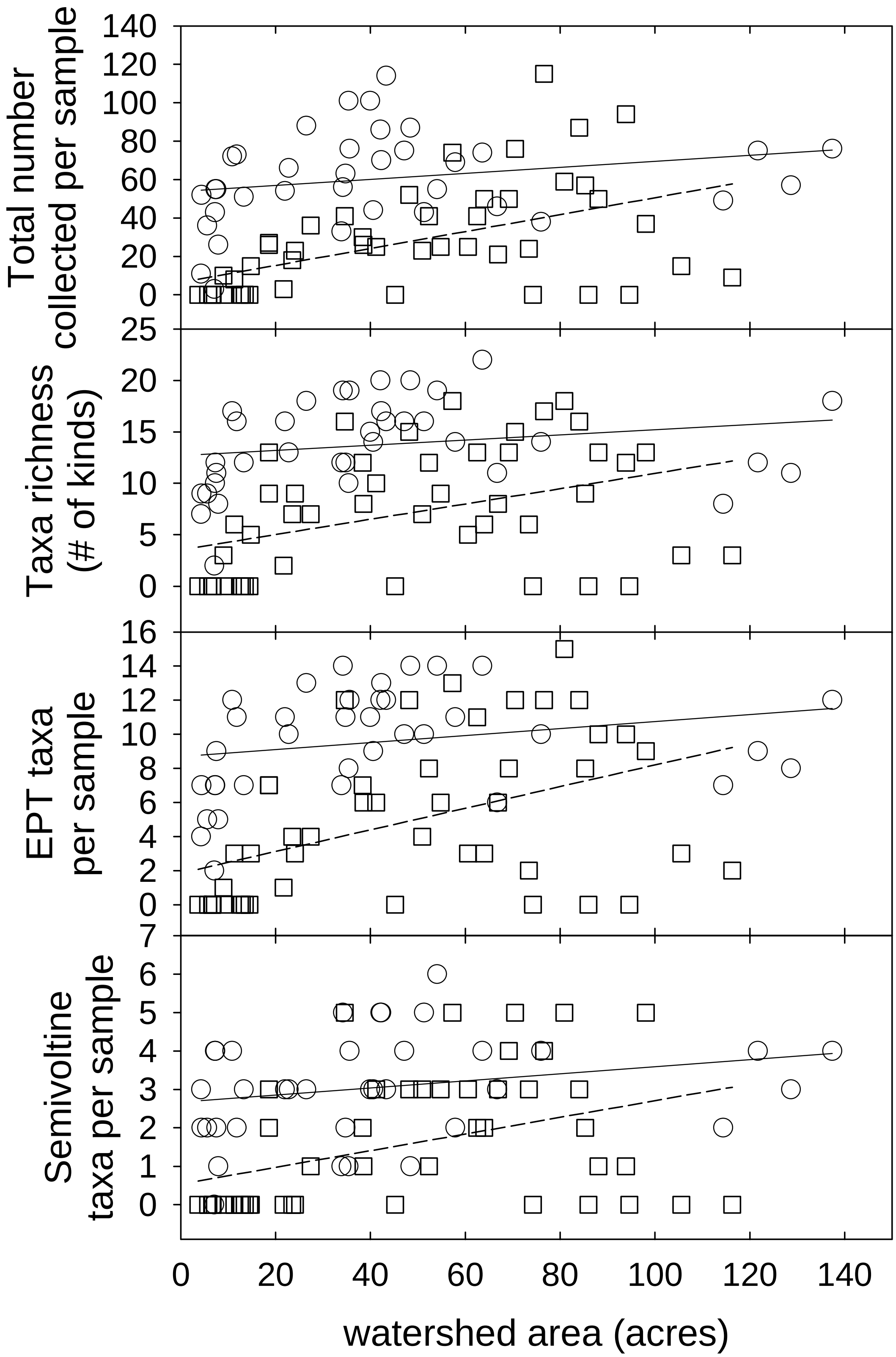


Figure 6. Profiles of biological attributes versus watershed area of longwall mined (squares) and reference streams (circles). Least squares means linear regression lines for longwall mined (dashed, N=48) and reference (solid, N=40) streams.

Table 5. Taxa collected in order of abundance during the study showing taxonomic affiliations, life cycle (univoltine=completes life cycle in 1 year, and semivoltine=two-year or longer aquatic larval development period), and functional feeding group assignment.

class or insect order	*Genus (species)*	life cycle	function
Ephemeroptera	*Paraleptaphlebia*	Univoltine	predator
Plecoptera	*Leuctra*	Univoltine	shredder
Trichoptera	*Diplectrona*	Univoltine	collector
Plecoptera	*Agnetina*	Semivoltine	predator
Ephemeroptera	*Heptagenia*	Univoltine	grazer
Plecoptera	*Peltoperla*	Semivoltine	shredder
Decopoda	*Cambarus*	Semivoltine	shredder
Plecoptera	*Amphinemura delosa*	Univoltine	shredder
Trichoptera	*Neophylax*	Univoltine	grazer
Ephemeroptera	*Stenonema*	Semivoltine	grazer
Amphipoda	*Gammarus*	Univoltine	shredder
Trichoptera	*Lepidostoma*	Univoltine	shredder
Ephemeroptera	*Baetis*	Univoltine	collector
Trichoptera	*Pycnopsyche*	Univoltine	shredder
Megaoptera	*Nigronia serricornis*	Semivoltine	predator
Isopoda	*Isopoda*	Univoltine	shredder
Plecoptera	*Acroneuria carolinensis*	Semivoltine	predator
Diptera	*Dicronota*	Univoltine	predator
Diptera	*Dixa*	Univoltine	collector
Plecoptera	*Isoperla*	Univoltine	predator
Plecoptera	*Perlesta*	Semivoltine	predator
Diptera	Chironomidae	Univoltine	collector
Plecoptera	*Ostracerca*	Univoltine	shredder
Ephemeroptera	*Ameletus*	Univoltine	collector
Diptera	*Limnophora*	Univoltine	collector
Diptera	*Tipula*	Univoltine	shredder
Coleoptera	*Dubiraphia*	Univoltine	collector
Plecoptera	*Sweltsa*	Semivoltine	shredder
Trichoptera	*Polycentropus*	Univoltine	collector
Ephemeroptera	*Epeorus*	Univoltine	grazer
Trichoptera	*Cyrnellus*	Univoltine	collector
Trichoptera	*Rhyacophila*	Univoltine	predator

Table 5 (cont.). Taxa collected in order of abundance during the study showing taxonomic affiliations, life cycle (univoltine=completes life cycle in 1 year, and semivoltine=two year or longer aquatic larval development period), and functional feeding group assignment.

class or insect order	*Genus (species)*	life cycle	function
Diptera	*Hexatoma*	Univoltine	predator
Annelida	*Oligochaeta*	Univoltine	collector
Ephemeroptera	*Ephemera*	Semivoltine	collector
Ephemeroptera	*Eurylophella temporalis*	Univoltine	collector
Molluska	*Gastropoda*	Univoltine	grazer
Coleoptera	*Dytiscus*	Univoltine	predator
Trichoptera	*Wormaldia*	Univoltine	collector
Odonata	*Cordulegaster*	Semivoltine	predator
Diptera	*Eubriidae*	Univoltine	predator
Megaloptera	*Sialis*	Univoltine	predator
Trichoptera	*Dolophilodes*	Univoltine	collector
Diptera	*Hydroporinae*	Univoltine	collector
Diptera	*Ormosia*	Univoltine	collector
Odonata	*Calopteryx*	Semivoltine	predator
Odonata	*Stylogomhus*	Semivoltine	predator
Diptera	*Hydrocantus*	Univoltine	predator
Diptera	*Stratiomys*	Univoltine	predator
Molluska	*Bivalvia*	Univoltine	collector
Plecoptera	*Clioperla clio*	Univoltine	predator
Trichoptera	*Hydropsyche betteni*	Univoltine	collector
Odonata	*Aeshna*	Univoltine	predator
Coleoptera	*Dytiscidae*	Univoltine	predator
Diptera	*Helochares*	Univoltine	collector
Diptera	*Hydroptilidae*	Univoltine	collector
Coleoptera	*Psephenus*	Univoltine	grazer
Diptera	*Limnophila*	Univoltine	predator
Diptera	*Simulium*	Univoltine	collector
Diptera	*Tabanus*	Univoltine	predator
Corixidae	*Corixa*	Univoltine	predator

Community function

Co-existence of the diverse taxa in these communities at any one time indicates a need for resource partitioning by specialization into various functional roles. Leaf shredders (36 and 37%) and fine particle collectors (40 and 35%) comprised the bulk of the community function in both disturbed and reference streams (Table 6). Only 13-14% of the communities in all streams were engaged in grazing biofilm (algal and fungal matrix) from the stream bottom. There were no significant overall differences in longwall mined versus reference streams in the proportional allocation of functional feeding groups. However, the variability within streams, as indicated by high standard deviations (Table 6) and box plot ranges (Figure 7) was consistently greater in longwall mined streams. In longwall mined streams the proportion of shredders, collectors, grazers, and predators were more widely ranging than in reference streams.

Whereas the mean functional disposition of longwall mined versus reference streams was not significantly different (Table 6), the pattern of change in community function along the stream gradient was significantly different (Figure 8). For instance, in reference streams shredders comprised 47% of the community in the upper stream reaches (10 acres) and declined to less than 30% of the community in larger streams draining the lower reaches of 100+ acre watersheds ($p<0.01$, $r^2=0.17$). The precipitous decline in shredder dominance was compensated for by subsequent increases in the collectors and grazers. In longwall mined streams these patterns failed to emerge. In longwall mined streams shredders were often most abundant in the mid-reaches of watersheds, apparently corresponding with resurgence of water into a streambed. Shredders populations were independent of watershed area and much less predictable in longwall mined streams compared to reference streams. Longwall mined streams had greater functional imbalance compared to reference streams, and they failed to achieve significant changes in functional allocations witnessed along the gradient of reference streams (Figure 8). The predator fauna comprised, on average, approximately 11-14% of the communities in streams. However, predators were absent or nearly absent in many sites in longwall mined streams.

Table 6. Mean (and 1 Standard Deviation) of biological community functional metrics where macroinvertebrate communities were present in samples from longwall mined (N=34) versus reference (N=40) watersheds (ANOVA, Dunnett's Test, *p<0.01).

Functional feeding group (% of total number collected)	Reference streams Mean	Reference streams (SD)	Longwall mined streams Mean	Longwall mined streams (SD)
Leaf shredders	37	(15)	36	(23)
Fine particle collectors	35	(12)	40	(23)
Grazers	14	(9)	13	(10)
Predators	14	(11)	11	(13)

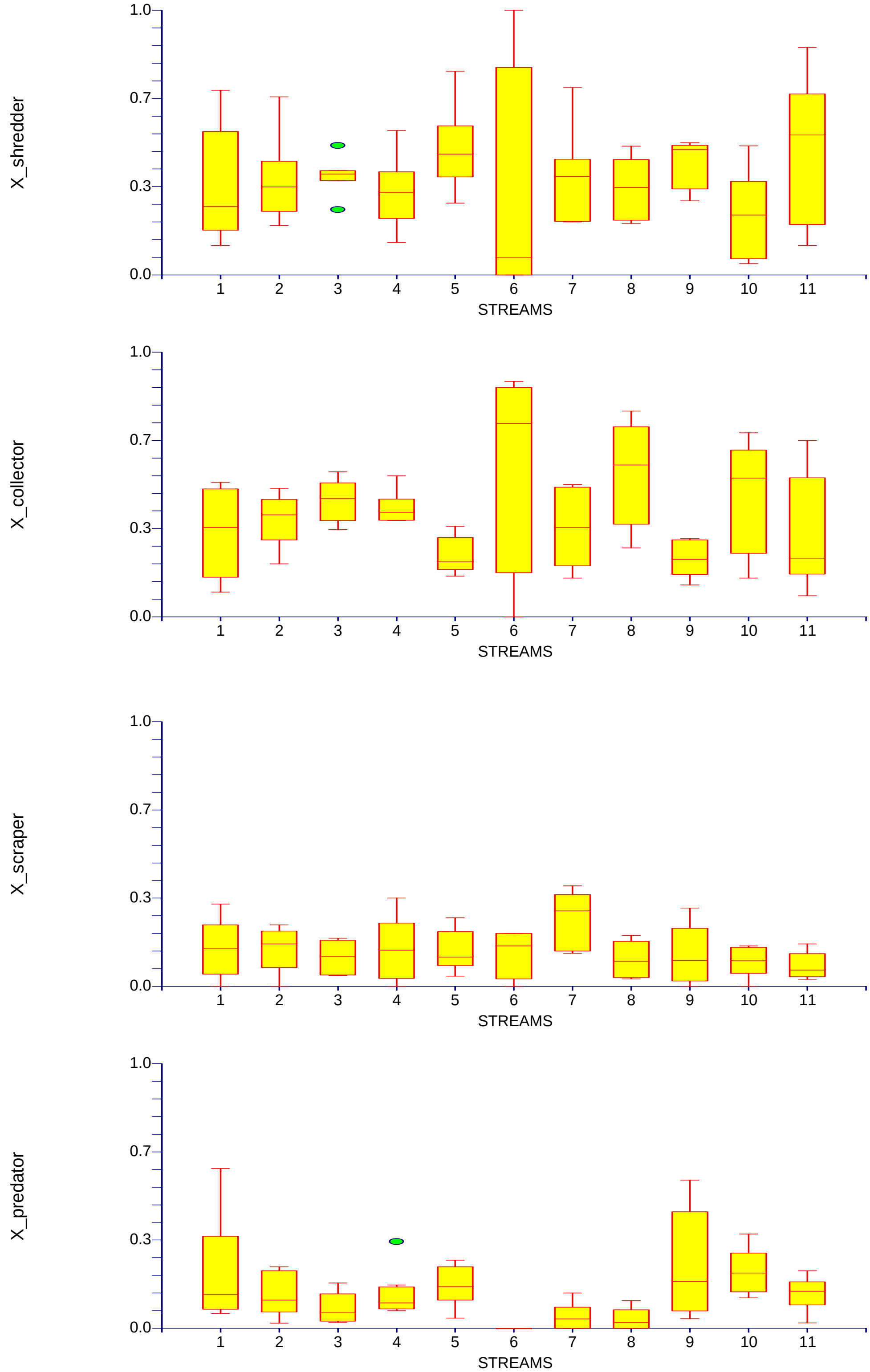


Figure 7. Box plots of median functional feeding group proportions in samples (N=8) from reference streams in Dysart Woods (streams 1-2) and Marshall County (3-5), and longwall mined streams that were recently longwall mined (6-8) or had been longwall mined over the past decade (9-11) in Marshall County.

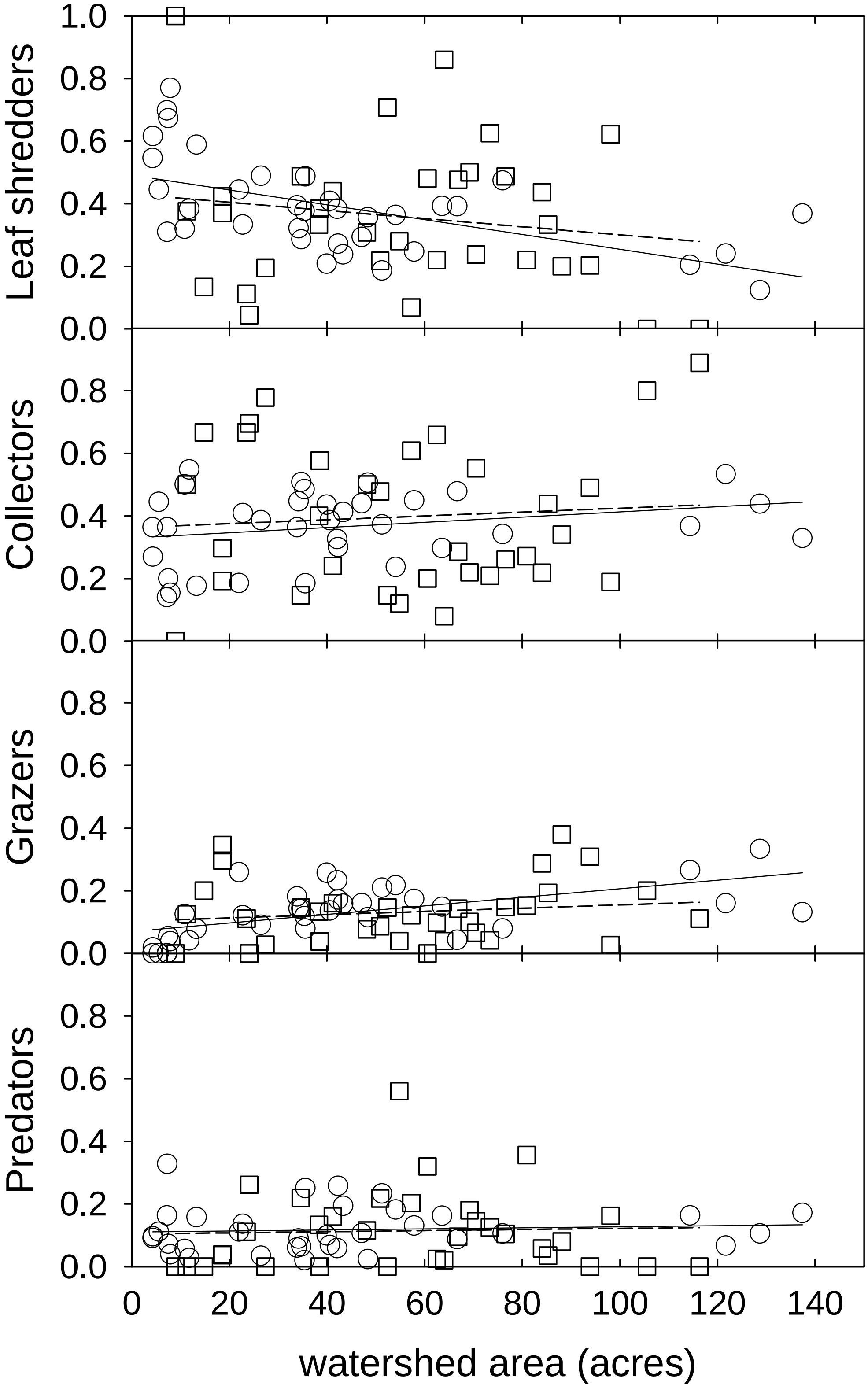


Figure 8. Profiles of functional feeding group proportions versus watershed area of longwall mined (squares) and reference streams (circles). Least squares means linear regression lines for longwall mined (dashed, N=48) and reference (solid, N=40) streams.

Taxa specific responses

Predominant macroinvertebrate taxa were plotted against watershed area to determine if any taxa-specific patterns emerged with respect to disturbance. The mayfly *Paraleptophlebia* was the most abundant organism in the study (Table 5). *Paraleptaphlebia* was collected at all reference sites, and was most abundant in the upper reaches of reference streams (Figure 9). *Paraleptaphlebia* was not abundant in the headwater reaches of most longwall mined streams, but was abundant at specific sties downstream. The return of *Paraleptophlebia* to the lower reaches of longwall mined streams appeared to coincide with re-emergence of sunken streams. *Paraleptophlebia* reached peak abundance in 10-50 acre reference streams compared to 60-100 acre longwall mined streams.

The stonefly *Leuctra* was the second-most abundant organism in the study, was collected at 85% of reference stream sites, and was most abundant at sites closest to the stream source. In longwall mined streams, however, *Leuctra* was virtually absent from the upper reaches of longwall mined streams, and peak abundance occurred at 5 specific sites further downstream in 80-100 acre, recently mined watersheds. *Leuctra* was nearly absent from streams that had been longwall mined several years prior to the study. Only one or two *Leuctra* were collected, and from only 5 of the 24 sites in streams that had been longwall mined in the past.

Diplectrona was the dominant caddisfly in headwater streams in this study (Table 5). *Diplectrona* is a net-spinning caddisfly that filter-feeds on suspended particulate matter in streams. *Diplectrona* were abundant in the upper reaches of most reference streams and common in the mid and lower reaches of all reference streams. *Diplectrona* were generally less abundant in longwall mined streams, and nearly absent from the recently disturbed streams.

The stonefly *Agnetina*, the mayfly *Heptagenia*, and the stonefly *Peltoperla* each showed a consistent bimodal distribution when comparing longwall mined versus reference streams (Figure 10). In reference streams these organisms dominate the upper reaches of streams. In contrast, these taxa are abundant only in the lower eaches of longwall mined streams. These organisms respond to dewatering of the upper reaches by inhabiting downstream resurgence areas of some streams much as they would a reference headwater spring seep. However, other taxa, such as *Lepidostoma* (Trichoptera: Lepidostomidae), the 12th most abundant organism collected, were common in reference streams but rare in longwall mined streams and did not exhibit the “resurgence pattern.” Obviously, several taxa appear to be at disproportionate risk due to longwall mining. Other taxa, specifically isopods and amphipods, may actually benefit because they are associated with upwelling of stream water downstream of subsided stream segments (Figure 11). The question that arises is can these longwall mined streams, given the loss of a tremendous amount of habitat, provide adequate refuge to maintain regional populations of headwater stream-dependent organisms.

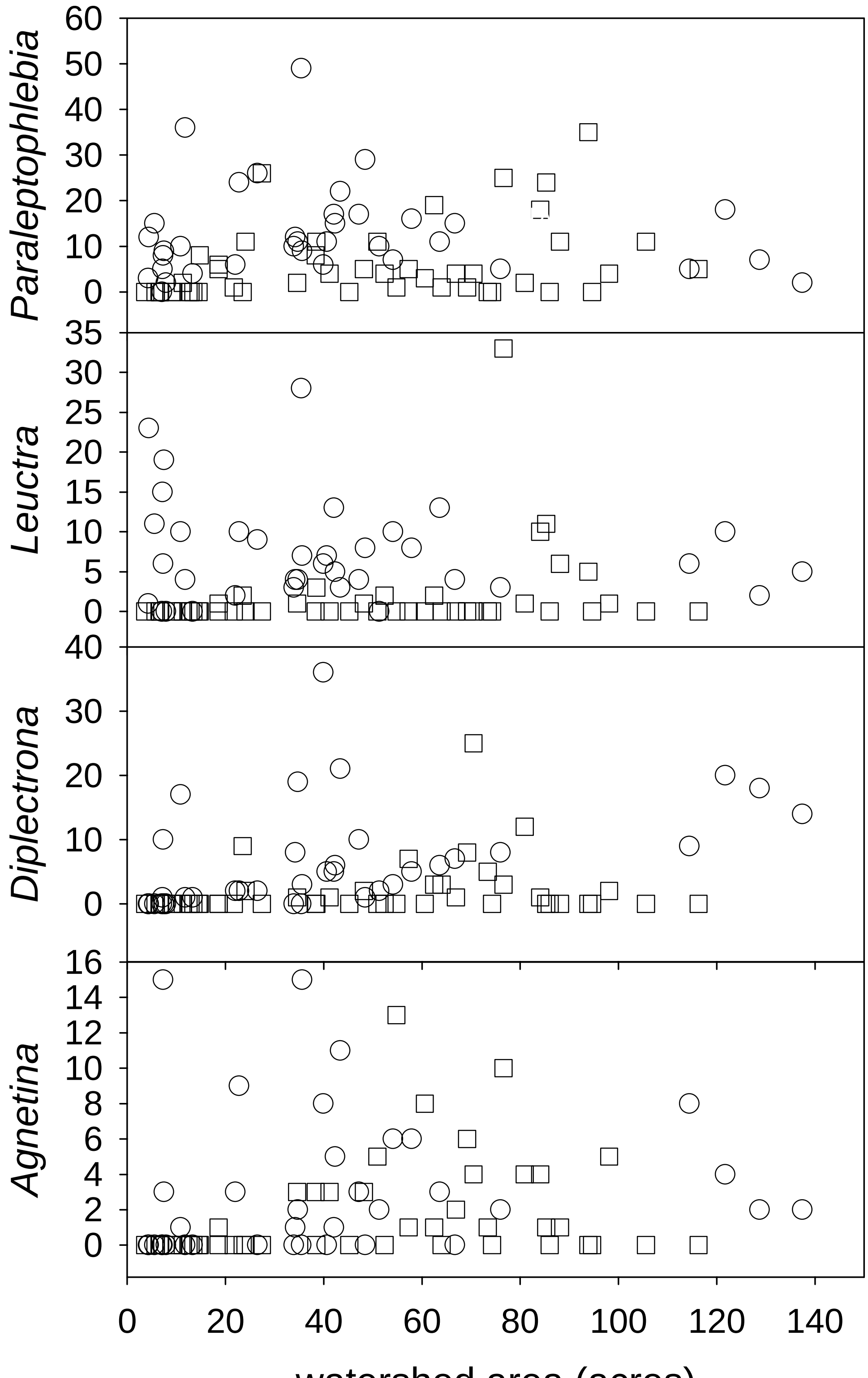


Figure 9. Profiles of the four most abundant taxa showing the number collected per sample versus watershed area of longwall mined (squares) and reference streams (circles).

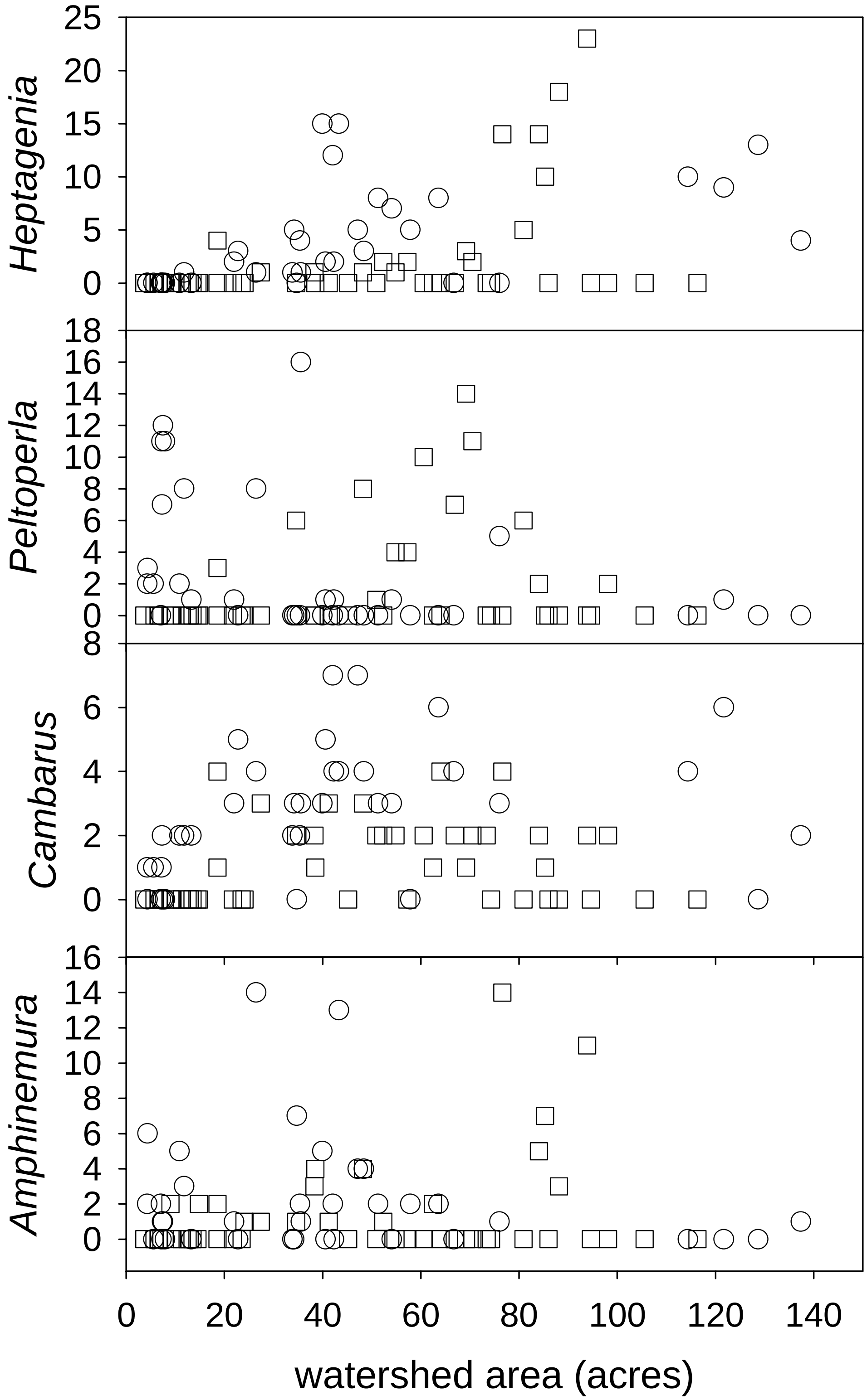


Figure 10. Profiles of the 5th through 8th most abundant taxa showing the number of individuals collected per sample versus watershed area of longwall mined (squares) and reference streams (circles).

Ubiquity of macroinvertebrate taxa

Widespread occurrence, omnipresence, or ubiquity of macroinvertebrate taxa was measured mathematically by formulating a Ubiquity Index. The Ubiquity Index value indicates the percent chance of finding an organism at any random site in a regional headwater stream. Ubiquity Index values were compared between disturbed and reference conditions (samples, streams, and regions) to determine the degree to which longwall mining affected regional macroinvertebrate distribution, and to assay for any taxa-specific responses.

As a group, the EPT Taxa (mayfly, stonefly, caddisfly) were omnipresent in reference streams. Stoneflies were collected in every reference stream sample (Table 7). Mayflies were present in all but one, and caddisflies were present in all but 2 of the 40 reference samples. Omnipresence of multiple EPT Taxa is perhaps the best indicator of perennial stream communities in the region. Additionally, Semivoltine Taxa, those requiring permanent aquatic conditions, where collected at 98% of reference sites.

The consistent presence of long-lived aquatic taxa across the region indicates perennial aquatic conditions originating at the stream source in watersheds draining areas as small as 5 acres. Spring seeps at the point of flow origin continue downstream as permanent water contiguous with the larger stream and river ecosystems indicated on USGS 1:24,000 scale data. It should be noted that, based on the biota, perennial aquatic conditions exist at all reference sites even though only 25% of sites were indicated as perennial streams designated by solid blue lines on USGS 1:24,000 scale data. Of the remaining reference stream samples, 2% were indicated as “intermittent” streams (dot-dash blue line) and 73% were not shown on USGS 1:24,000 scale data, and are often mistakenly referred to as “ephemeral” streams. In light of the ubiquitous biological community presence in streams in small watersheds across the region; the USGS 1:24,000 scale data is inaccurate with regard to stream designation as well as stream delineation.

Table 7. Ubiquity Index values (U) for reference streams versus longwall mined disturbed streams for taxa summary variables.

Taxa summary variables	U reference	U disturbed	U difference
EPT Taxa	1.000	0.708	-0.292
Mayflies	0.979	0.667	-0.313
Stoneflies	1.000	0.625	-0.375
Caddisflies	0.948	0.583	-0.365
Semivoltine taxa	0.979	0.465	-0.514

Macroinvertebrate communities were not always present in longwall mined headwater streams. Seven of 24 sampling sites in recently mined streams and 7 of 24 samples from streams mined over the past decade had no surface water. Therefore, only 71% of the habitat available in reference streams was also available in analogous disturbed streams, and for any given taxa a generalized decline of 29% in the Ubiquity Index scores would be expected. A 67% Ubiquity Index score indicates that, with 2 exceptions, mayflies were present wherever surface water was present in longwall mined streams. Any further declines would indicate that macroinvertebrates in the remaining 71% of the habitat are further impared, such as in the case of stoneflies and caddiflies, each showing 37% reductions in Ubiquity following longwall mining (Table 7). Semivoltine taxa appeared even more sensitive with Ubiquity Index scores reduced from 98% to 47% following longwall mining impacts to regional watersheds, streams, and stream reaches.

Ubiquity of the EPT Taxa in disturbed streams is mostly due to the presence of the mayfly *Paraleptophlebia* (Ephemeroptera: Leptophlebiidae), the most abundant and widely-distributed macroinvertebrate in regional headwater streams. In the genus *Paraleptophlebia*, the time required for nymphal development varies from six-months to one-year depending on species and latitude (Edmunds, *et al*, 1976). Of the dominant mayflies studied, *Paraleptophlebia* was the least responsive in terms of decline in ubiquity following mining (Figure 11).

The Heptageniid mayflies (Ephemeroptera: Heptageniidae) *Heptagenia* and *Stenonema*, characterized by somewhat longer nymphal development periods (Wallace & Anderson, 1996), had proportional reductions in ubiquity of 46, and 47%, respectively. Likewise, the most abundant and ubiquitous stonefly in this study, *Leuctra*, characterized by 1-2 year aquatic nymphal development periods (Wallace & Anderson, 1996; Stewart & Stark, 1988), had a 65% proportional reduction in ubiquity across the region following longwall mining (Figure11).

The stonefly *Acroneuria carolinensis* (Plecoptera: Perlidae) has a well-documented two-year aquatic larval development period in streams (Wallace & Anderson, 1996). Although *Acroneuria* was the sixteenth most commonly encountered macroinvertebrate in reference streams with a ubiquity index value of 31%, it was nearly eliminated from longwall mined streams, with a Ubiquity Index value of 5% (Figure 11). The Dobbsonfly *Nigronia Serricornis* (Megaloptera: Corydalidae) has a three-year aquatic development period in West Virginia streams (Tarter, 1976), was the fifteenth most commonly encountered macroinvertebrate in streams as well as the dominant predatory macroinvertebrate. *Nigronia* exhibited 22% ubiquity in the longwall mined watersheds versus 59% ubiquity in reference streams. *Nigronia* were common at the source and in the upper reaches of reference streams. In longwall mined streams Nigronia was restricted to the downstream reaches where *Nigronia* appears to be a good indicator of the resurgence of perennial stream conditions in the lower reaches of some longwall mined streams.

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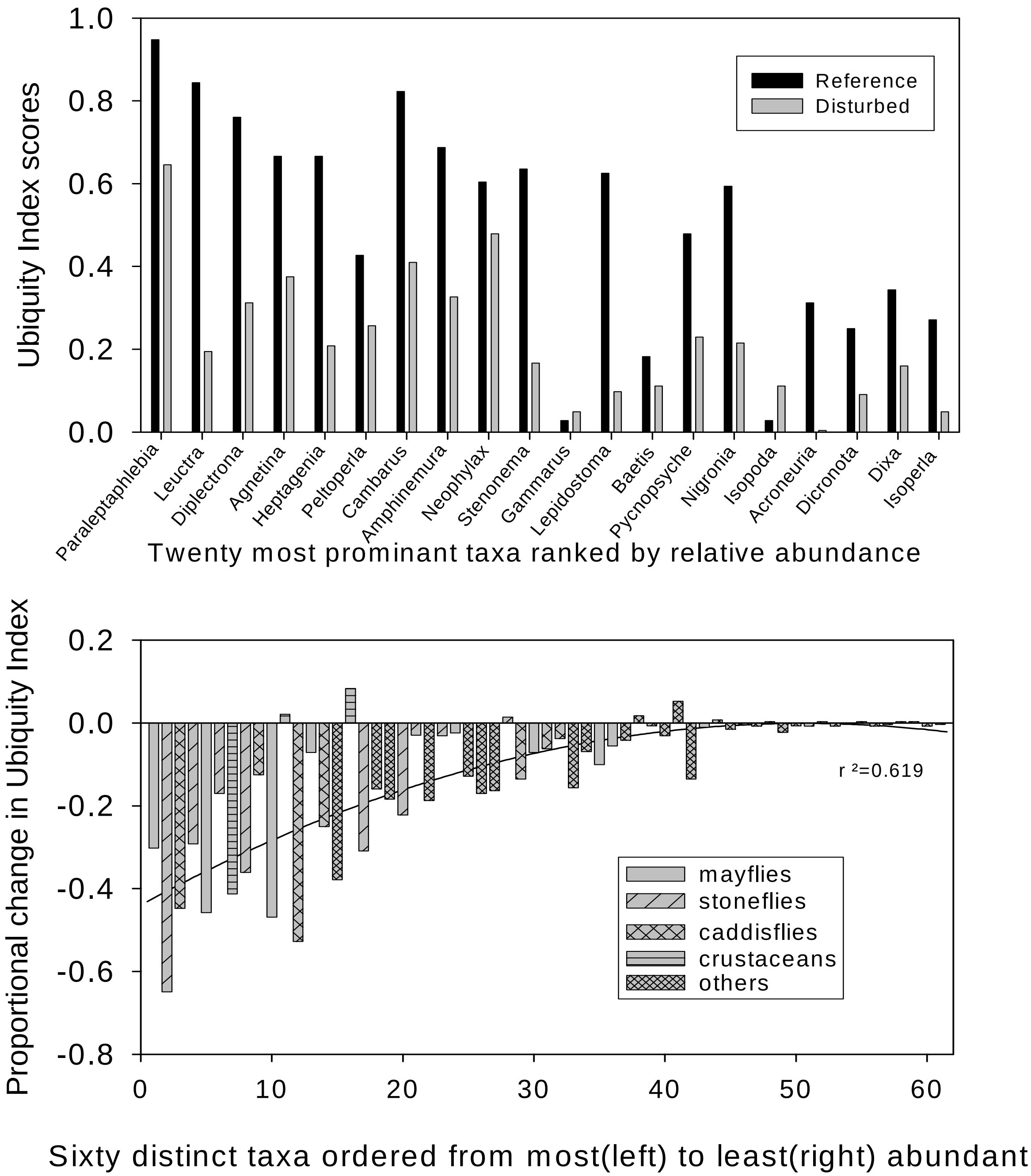

Figure 11. Comparison (top) of Ubiquity Index scores in disturbed versus reference conditions for the twenty most abundant macroinvertebrate taxa, and (bottom) the relationship (2[nd]-order polynomial regression, $p<0.001$) between the proportional change in Ubiquity following longwall mining versus the relative abundance of macroinvertebrate taxa across the region.

Discussion

The physical dimensions of the 5 reference and 6 longwall mined watersheds were comparable with the exception of water temperature and stream width. Instantaneous water temperature at the time of sampling indicated significantly lower surface water temperature in longwall mined versus reference streams. Water temperatures were lower even though sampling of longwall mined streams was chronologically interspersed with reference stream sampling. Loss of water at the surface and longer underground residence time resulted in 1–2^{o}C lower summer water temperatures in longwall mined streams.

Longwall mined streams were dry at 29% of study sites, most of which were within 100m of the point of flow origin. If dry streams with zero width were removed from the model, median stream width was not significantly different when comparing longwall mined streams with reference streams. However, where surface water did exist in longwall mined streams, streams were on average 2/7 the width of comparable reference streams. Recovery of surface flow in longwall mined streams occurred, as indicated by median stream widths compared to reference conditions, on average, in approximately 80 acre watersheds.

Three of five chemical measures showed significant differences when comparing longwall mined versus reference streams. Higher total dissolved solids, alkalinity, and oxygen demand are typical impacts associated with mining. Stream water quality was somewhat degraded as evidenced by higher conductivity in longwall mined streams. However, the presence of carbonate minerals in fractured rock strata helped buffer the dissolution of pyritic materials, thus pH remained similar to reference conditions.

Within the biological community the EPT Taxa represented 28 of the 60 kinds of macroinvertebrates collected, and 3,265 of the 3,932 total number of macroinvertebrates collected in this study. One can expect to collect between 6 and 14 different EPT Taxa at any site in any reference stream 95% of the time. The EPT Taxa are often used as indicators of good water quality because as a group they are particularly responsive to disturbance (Rosenberg & Resh, 1993). In this study the primary interest in EPT Taxa is their relatively long aquatic larval development period. With some exceptions, EPT Taxa typically require greater than 9 months residence in streams in order to complete their larval development and successfully emerge as adults (Wallace & Anderson, 1996). The co-existence of multiple EPT Taxa in these streams in the summer months is indicative of their permanence as consistent landscape elements. These streams, often mistakenly referred to as “ephemeral” or “intermittent” because of their inaccurate depiction on USGS 1:24,000 scale data, are indeed perennial entities.

The difference in the response of EPT Taxa, with a 29% proportional reduction in ubiquity following longwall mining, versus Semivoltine Taxa, with a 51% proportional reduction in ubiquity, was approximately 22%. The dynamic changes in headwater stream communities indicate that 29% of perennial headwater streams are “dewatered,” lasting a few weeks at most following a storm event, sometimes providing isolated pockets of refuge, but incapable of supporting a sustained aquatic community. An additional 22% of longwall mined streams are “partially dewatered,” supporting organisms with up to 9 month life cycles but failing to provide suitable conditions for the perennial macroinvertebrate communities observed in reference streams. Longwall mining results in a 50% reduction in the omnipresence of perennial aquatic biological communities in headwater streams across the region.

In many regions headwater streams harbor biodiversity that equals or exceeds that of larger downstream reaches (Feminella, 1996; Dieterich & Anderson, 2000; Williams, 1996). Many species live only in headwater streams, and loss of headwaters represents a significant threat to southern Appalachian fauna (Morse *et al*, 1993). Many other forest species depend on the close proximity of streams directly as breeding sites and water sources, and indirectly, for instance, the emergence of aquatic insects providing a high quality a food source in a form and at a time suitable for breeding birds. Loss of one-half of all headwater streams from the longwall mining region may have significant consequences for central Appalachian forest ecosystems.

Conclusion

Longwall mining results in a net loss of one-half of all headwater streams in Marshall County, West Virginia. Streams are particularly impacted near the source, and re-emerge downstream. Otherwise, aquatic macroinvertebrate communities in reference streams are ubiquitous across the region, rich in diversity, long-lived, and dependent on the surrounding terrestrial ecosystems for energy and nutrients.

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